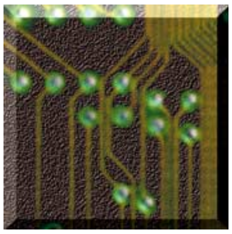

Expanding Mechanical Design and Fabrication Horizons

Dale W. Wilson, Leslie E. Bailey, and *Clifford E. Bennett*

The capability to develop prototype hardware systems is improving steadily as computer technology is dramatically enhancing design, fabrication processes, and tools. Designers now make extensive use of sophisticated 3D solid modeling programs to visualize design concepts, perform engineering analysis, and communicate detailed design data through networked file transfers. Numerically controlled computerized machine tools are then programmed using the design data to produce parts faster and with greater accuracy than ever before. New laser machining, electrical discharge machining, and rapid prototyping technology are enabling the fabrication of small, precision components not possible using traditional methods. The result is faster product development cycle times and lower costs. (Keywords: Casting, Computer-aided design, Computer-aided machining, Electrical discharge machining, Finite-element analysis, Laser machining, Rapid prototyping.)

INTRODUCTION

At this dawn of the 21st century, the key challenges facing engineers responsible for the development of prototype mechanical hardware systems have expanded beyond the purely technical realm. Today research engineers must creatively deliver increasingly complex instruments and systems in less time and at lower costs than ever before. This trend is expected to continue well into this century as industry attempts to capitalize on emerging computational and information technologies. To remain competitive in meeting these challenges, the Mechanical Services Group (TSM) of the Engineering, Design, and Fabrication Facility within the Technical Services Department (TSD) has implemented a continuous stream of evolutionary improvements in mechanical design and fabrication methods that take advantage of emerging computer modeling, display, control, information management, and materials fabrication technologies.

Product development is an iterative yet creative process linking design and fabrication processes. Improvements in the product design process have occurred through the use of more efficient tools, enhanced communications capabilities, and design and fabrication process improvements. Most of these enhancements have been powered by the rapidly increasing capability of affordable computer technology.

While the improvements in design and fabrication automation have been evolutionary, the collective impact of these changes has the potential to be revolutionary if used to full advantage. To better understand how this revolutionary improvement in product development can be achieved, this article describes the significance of the key advancements in design, analysis, and fabrication tools and how they interact to reduce design cycle times and development costs.

THE PRODUCT DEVELOPMENT PROCESS

Product development is a complex process that can be realized in many different ways. A simple block diagram of a prototype product development process is shown in Fig. 1. The process defines how ideas are turned into a physical prototype by repeatedly following an ordered sequence of steps. The arrows show how concepts and solutions from each stage are evaluated and redone, if necessary, to achieve the design requirements. There are three ways to significantly reduce product development times and costs: (1) shorten the time it takes to perform each step in the process, (2) reduce the number of iterations in the design process, and (3) conduct steps in a parallel, substantially overlapping mode instead of in series. This third "holistic" approach[1] has the most dramatic impact on development cycle times by accelerating the whole process.

The process steps most significantly impacted by the advanced features and capabilities of new computer-based design tools are shown in yellow (Fig.1), while those impacted by advanced fabrication capabilities are shown in blue. Much of the design process can now be achieved in "virtual" space using 3D solid modeling, analysis, and mechanical simulations. Computer design and analysis tools enhance the visualization of concepts, speed up the evaluation of expected performance, and streamline communication of design information. Design concepts and variations can be explored on the computer screen, *before* prototype hardware is fabricated. For small, simple development efforts, savings in time and cost are small, but for larger, more complex programs, time and cost savings can be exponentially more significant. Experience has shown that gains in efficiency achieved by using modern computer-aided design (CAD) tools can quickly be erased by increases in design iterations if the design process is loosely controlled.

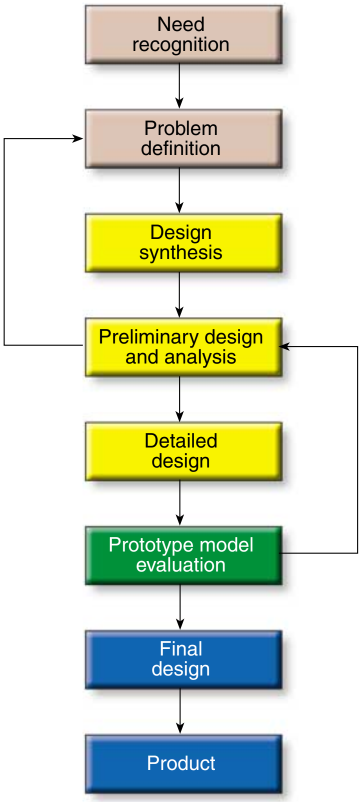

Figure 1. Simplified schematic block diagram showing the key steps in a typical linear prototype product development process.

The savings are especially significant when the design process is linked to the fabrication process. Once a design has been introduced into the fabrication stage, further changes to it become very costly. Also, some designs are easier and more cost-effective to produce than others, and the practice of "design for manufacture" takes on a more significant role in performing cost-effective prototype fabrication. Effective design for manufacture requires collaboration among engineers, designers, and fabricators early in the conceptual design stage. Inherently this process generates change, and the modern computer design tools minimize the impact of such changes. Advances in design tools have contributed to the efficient and successful design support of the Near Earth Asteroid Rendezvous (NEAR),[2] Advanced Composition Explorer (ACE) and Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) spacecraft, the Seafloor Characterization and Mapping Pod (SCAMP), and the highly publicized Integrated Storage System developed for the Advanced Natural Gas Vehicle (ANGV) Project.[3]

ADVANCED DESIGN TOOLS

CAD and Solid Modeling Tools

State-of-the-art CAD systems offer many advantages to the design team. Concepts can be generated and analyzed in a virtual environment, and digital images can be enhanced to display photorealistic renderings. Many design concepts and variations can be explored on the computer screen, and any changes can be captured automatically and implemented quickly. Animation and simulation software can be applied to explore mechanical characteristics of mechanisms for motion paths and interferences. Moreover, designs are stored as computer data files that can be used as a starting point for future revisions of hardware. Solid modeling greatly enhances the designer's ability to create and manipulate assemblies. The volume, mass, center of gravity, and moments of inertia can be calculated by the CAD program by assigning appropriate properties to the solid. Geometric interference can also be quickly assessed and quantified to check tolerances. Cutaway views can be generated (Fig. 2) to show hidden detail. These capabilities facilitate the more efficient evolution and understanding of complex hardware designs.

TSD currently uses Parametric Technology Corporation's Pro/Engineer (Pro/E) software, which is powerful, fast, and robust. Changes to the computer representation of the hardware are made by merely retyping a dimension. In Pro/E, related geometry, dimensions, and numerically controlled (NC) programming information are all driven by parameters. When a parametric change is made, the associated downstream data are updated automatically. Parametric means that geometry changes are driven by predefined physical parameters such as length, width, and height. Both the initial design and later modifications can be created with record efficiency. In addition, the parametric information is associative, i.e., the numbers used to create the original geometry stay with the part in downstream tasks such as detailing and analyzing. When a parameter is modified in the 3D part, the 2D details are updated as well. The reverse is also true. This automated associativity for updating data is a major advancement in CAD software. In addition, this software supports library parts, automated bills of material, and large assembly management through the use of skeleton parts and simplified representations.

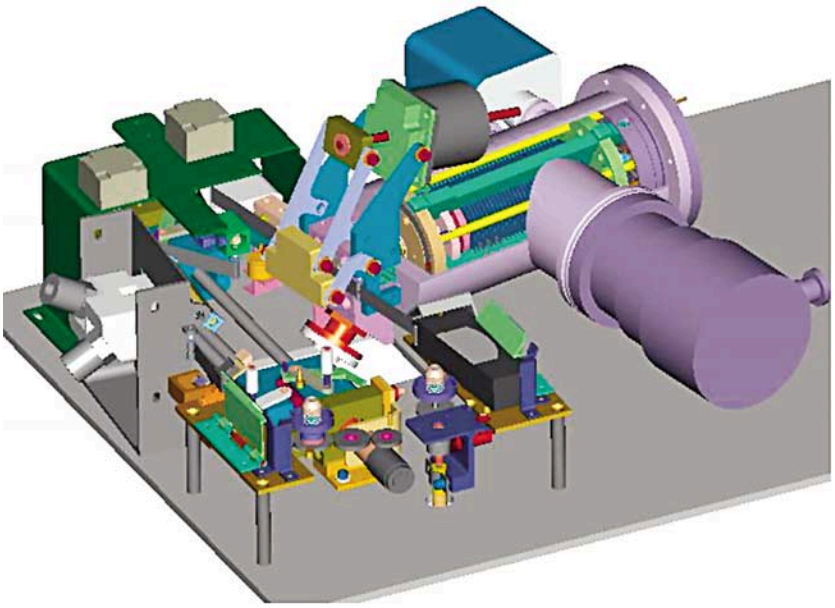

Figure 2. Solid model of a mini-mass spectrometer showing the power of the cutaway view feature in revealing hidden geometric details of designs.

Product Data Management

Product data management (PDM) systems provide a means for organizing and storing the CAD files produced by a design so that they can be accessed for future use. This capability is absolutely essential for configuration-managed design to preserve the CAD databases and associated documentation and to promote disciplined, formal communications of design information. Currently, all drawings and design databases are archived in an Oracle-based PDM system. As long as the databases are compatible with the current software in use, the information can be retrieved and reused by the CAD package as a basis for new or modified designs. In addition, the drawings are archived in a neutral plotter format so that they can be displayed and replotted well into the future as read-only files. The PDM stores all types of data, allowing the archiving of memos, special assembly instructions, and reports generated for a program. This ancillary information can be very valuable in preserving important insights about a design, especially if it is going to be used again. Since APL often uses design heritage to reduce time and costs, the PDM is an important tool to ensure that important design information is not lost.

Engineering Analysis Tools

Whereas CAD has significantly enhanced the communication of design information, modern computer-aided engineering (CAE) tools such as finite-element modeling (FEM) have revolutionized design evaluation. Until the advent of modern numerical analysis tools, it was not possible to analyze parts or structures in their full geometric complexity, including realistic boundary constraints and loading conditions. Most analyses were approximate and relied heavily on the mechanical evaluation of design elements, such as bolted joints, thickness transitions, and cutouts, required in practical designs. This empirical characterization was expensive and time-consuming. Under these conditions, there was a tendency to design conservatively to minimize risk, costs, and design cycle times.

The introduction and refinement of FEM over the last two decades have enabled engineers to accurately analyze parts with complex geometry, subject to a realistic simulation of boundary constraints and loading conditions. Despite the capability offered by FEM, for many years it was used very sparingly because it was time-consuming and costly, requiring expensive software and mainframe computing facilities. In the last decade, the widespread access to powerful, low-cost computing and graphics display capability has made FEM a practical and widely used analysis tool. User-friendly software featuring pre- and postprocessors has made it easier to create part geometries, generate meshes, input properties and loading conditions, and display results.

In finite-element analysis, complex geometry parts are analyzed by discretizing the geometry into a mesh of simple, regular geometric elements (Fig. 3a). Once material properties are assigned to each element and boundary and loading conditions are applied at the boundaries, the governing equations are numerically solved for each element. Then these solutions are combined for each element to provide the total solution for the part. In structural analysis, stresses (Fig. 3b), strains, and deformed shape can be determined and displayed for interpretation (Fig. 3c). FEM modules are available for linear and nonlinear structural, forced-response, dynamic, thermal, electromagnetic, and fluid analysis. A range of element types is also available to handle special geometric or analytical requirements. By matching the appropriate elements to the needs of the analysis, the specified accuracy is attained while minimizing run times and cost. There are numerous commercial FEM software packages available, and APL has widely used COSMOS, NASTRAN, and ABAQUS for its analyses.

Pro/Mechanica, the FEM module in Pro/E, allows the integration of solid models in Pro/E with FEM analysis. Pro/Mechanica offers features that enable automated mesh optimization and automated design optimization. The program can be executed to change a part's geometry, iteratively resizing the structure and solving for the stresses until the part is optimized. The power of this process is amplified by the associativity between the model used for the analysis and the rest of the CAD drawing package. The newly sized part is captured in every other drawing in the package, from individual detail drawings to the top-level assembly drawing. This flow-through connectivity minimizes the opportunity for error introduction during design cycle iterations.

An advantage of having FEM integrated into the design tools is promoting design optimization early in the design process. Analysis is critical in supporting radical reduction in weight, minimizing materials required, and improving design for manufacture while assuring that the part will meet design requirements. It is important to ensure that the results of FEM analysis are valid for the geometry, materials, and boundary conditions representative of the design, because finite-element analysis is a numerical approximation method.

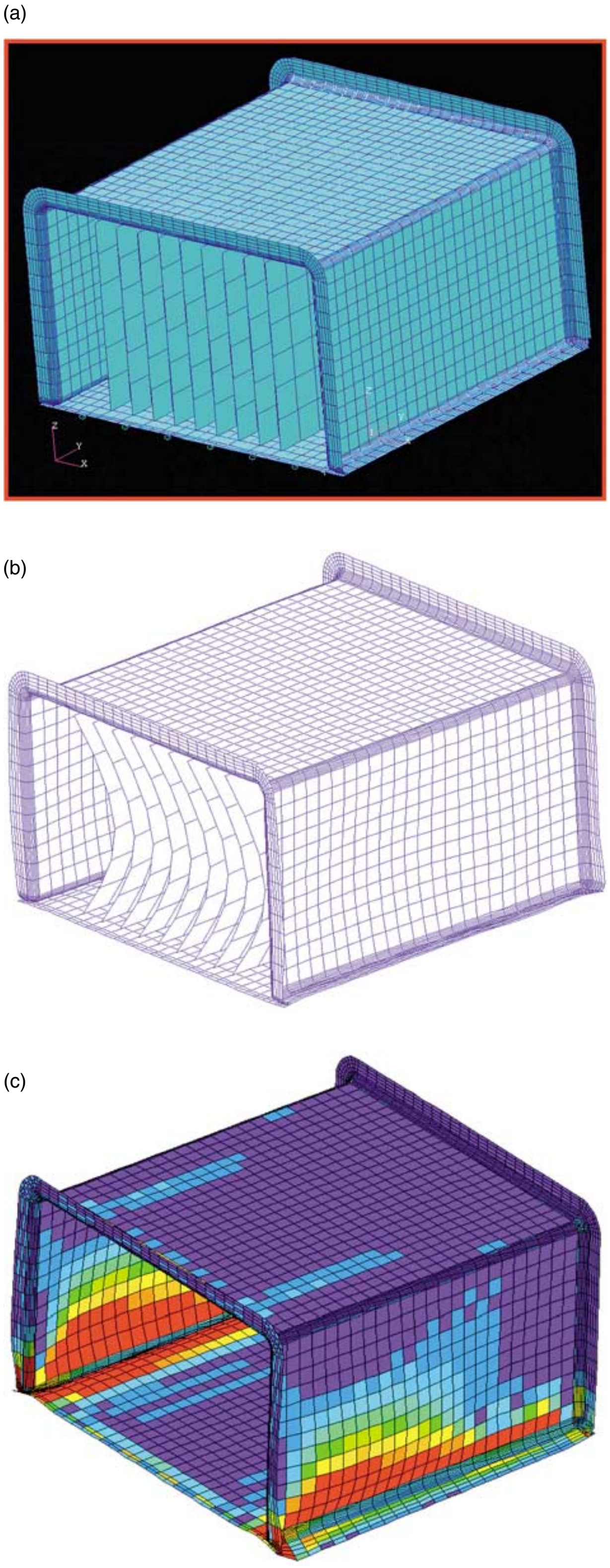

Figure 3. Finite-element model of a composite electronics enclosure using laminated shell elements. (a) The part discretized into a mesh. (b) Mode shapes of the housing coupled to the electronics boards subjected to vibration at 164 Hz. (c) Deformed contour plot displaying the Tsai-Wu failure index resulting from an imposed *g* loading (red indicates locations of predicted structural failure).

The quality of the solution is affected by mesh geometry, especially element size and aspect ratio, in regions of high stress gradient. The mesh must be properly sized to ensure accuracy, and this is usually accomplished by decreasing the mesh element size until the solution converges to a set of stress values. Automation of this process has made analysis easier to perform and simultaneously has increased the importance of analysis validation.

ADVANCES IN MECHANICAL FABRICATION

Computerization and computer control have drastically changed the nature of mechanical fabrication and expanded the options for cost-effective hardware development. NC and computer numerically controlled (CNC) tools have continued to improve the capabilities and efficiency of machine processes over the last decade. Computer technology has fueled significant advances in three areas that have impacted capabilities at APL: file transfer between CAD and computer-aided manufacturing (CAM) programs, machine automation and tooling, and rapid prototyping.

Computer-Aided Manufacturing

TSD launched a significant modernization program in 1984 that marked APL's first serious commitment to full-scale NC machining capability. The impact of that modernization was the subject of a 1986 *Technical Digest* article[4] in which the capabilities and benefits of NC machining were thoroughly explained. Over the last 15 years, further improvements in CNC fabrication have evolved from improvements in the basic performance of machine tools, advances in controller technology, the addition of automation options, improved tool designs, and enhancements in CAM software. All of these improvements have significantly increased fabrication accuracy and productivity.

CAD/CAM Interface

The interface between the CAD database and CAM software has been steadily improving, thereby significantly increasing productivity and quality. This improved connectivity has made the use of CNC machine tools more cost-effective and practical for the prototyping environment. Computer networks now link the computers that develop the designs to the computers that control the machine tools. This link enables the CAD geometry data files to be transferred directly to the computer that prepares the control program used by the machine tool to fabricate a part.

For example, in fabricating the consoles for the Advanced Area Defense Commander (AADC) Program, the console design geometry was imported into FabriWIN (MetalSoft, Inc., Santa Ana, California), the special CAM program that converts the design into sheet metal layouts and develops the NC program for the turret punch to cut the shapes. The connectivity between the designer's CAD data and the sheet metal fabrication CAM program enabled the fabrication of seven standard consoles, a conference table, and a main battle-watch console in less than 2 months. More importantly, the CAM tools facilitated rapid response in modifications to the consoles that were required during installation.

Machine Tool Automation

Figure 4 shows an example of a modern CNC milling machine. It has an automated tool changer that holds up to 20 tools that can be addressed for use on a work piece without manual intervention. A 20-HP motor drives the spindle at speeds up to 7500 rpm, nearly double the speeds available on earlier NC machines. The higher horsepower motor allows practical use of the high (3.8 m/min) feed rates capable from the machine. The milling machine has a large, 125 × 50 × 50 cm workspace that is fully enclosed to contain chips and coolant spray during high-speed machining. It also has through-spindle coolant delivery and a programmable coolant nozzle that adjusts the coolant delivery point automatically to match the tool being used. All of these enhanced features combine to improve the accuracy and speed of the machining process.

Modern CNC machines also have advanced controller features that improve productivity and capability. Powerful macro programs can be run to automate repetitive machining operations, such as drilling complex hole patterns, or provide advanced functions such as rigid tapping and spiral milling. Advanced controllers minimize memory requirements, promote more

Figure 4. Modern CNC milling machine that includes a powerful controller, an automatic tool changer, and four-axis motion control.

efficient data storage and data transfer, and run longer programs faster.

Direct numerical control, which is now standard on newer CNC machining centers like the Haas V4 (Haas Automation, Inc., Oxnard, California), allows machines to be directly linked to the TSM network server via the MasterCam programming system. This link enables the programming and storage of very large CNC programs and the flexibility to remotely run CNC programs directly from a network server.

All these features greatly reduced the fabrication cost of 52 magnesium battery cell sleeves for the TIMED spacecraft (Fig. 5). The ≈13.7-cm-long × 10.7-cm-dia. sleeves had rectangular bosses on a cylindrical surface and angled flanges requiring a large surfacing program. The Haas's full four-axis capability, simultaneous cutting action, and automatic tool changer allowed the battery cell sleeves to be completed in one milling operation rather than four. Not only was time saved by reduced setups, but accuracy was improved in delivering 52 replicates under a tight schedule.

EDM Machining

Computer technology has contributed to the refinement of two important machining technologies: laser machining and electrical discharge machining (EDM). Both technologies are noncontacting, making them excellent tools for machining intricate geometries or meso- and microscale components that would not be possible with traditional tooling and machining processes. The improved resolution, accuracy, and quality of the EDM process for a wider range of materials is a direct function of the computer control of the spark generator and the motion control systems. Modern EDM machines employ sophisticated fuzzy logic controllers that integrate feedback constantly from the process to maintain precise control of the electrical discharge process. The two types of EDM machining used at APL are die-sinking and wire.

EDM technology has been effectively used to machine a wide range of mechanical components in conductive materials that would have been difficult, if not impossible, to machine using other technology. EDM is especially effective in machining very hard metals and alloys. It is the technology of choice to perform mesoscale (micro-level) machining of very small parts from standard metals and metallic alloys since it produces a much cleaner machined surface finish than a laser.

An example of mesoscale machining performed using EDM is shown in Fig. 6. This small needle was machined from a 127-μm outside diameter stainless steel tube stock. Each of the 50 parts had a point machined by cutting the tubing on a 45° angle and placing a cutout 0.5 cm from the point. Neither feature could have a burr or any debris pushed inside. Wire EDM is extremely effective in precision machining of deep draw parts like the hinge shown in Fig. 7 for the Cassini Orbiter collimator door. If completed by conventional machining, the magnesium part would have required 11 separate setups. The use of a combination of wire and die-sinking EDM machining processes required only four setups. The part would have taken significantly more fabrication time using a milling machine, and some features would have been impossible to machine without die-sinking EDM.

Laser machining is currently available only for microelectronics processes at APL.[5] Laser machining for mechanical fabrication is currently being outsourced.

Figure 5. A magnesium battery cell for the TIMED spacecraft that was fabricated using the four-axis machining feature of the Haas V4 milling center.

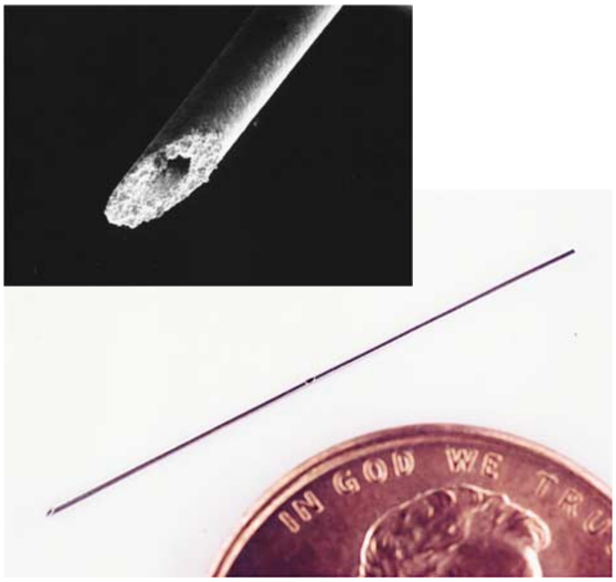

Figure 6. This 127-μm-dia. hypodermic needle was fabricated using EDM machining to cut a 45° angled point and to make a small cutout 0.5 cm from the tip. Both features had to be free of any burr or slag that might block the flow through the device.

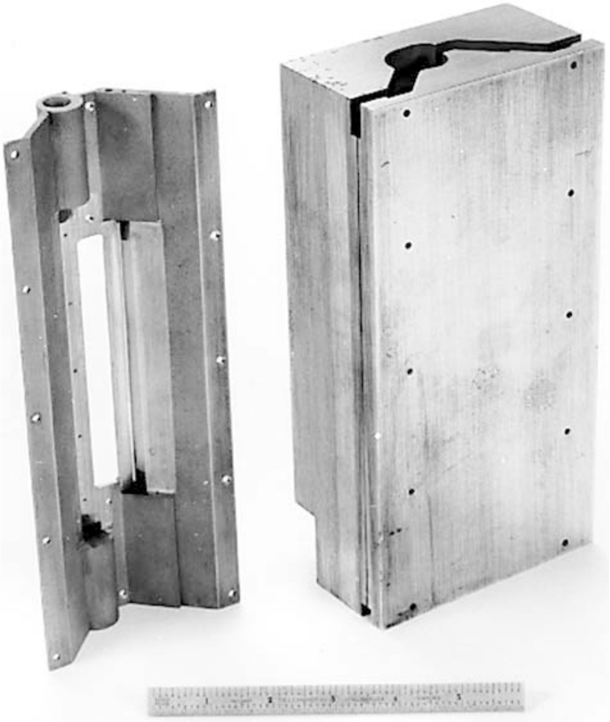

Figure 7. This Cassini collimator door hinge was produced using both wire and die-sinking EDM. The basic deep draw shape of the hinge was made very efficiently by using a single wire EDM cut. Some of the undercutting to make interior bearing seats could not have been done using conventional machining.

Studies are in progress to determine whether an in-house capability should be installed. Several of the sheet metal parts for the AADC consoles were fabricated by laser machining, and the quality and time to fabricate were compared with identical parts fabricated using the turret punch. The laser parts had excellent edge quality and were cut at 254 cm/min, resulting in a fabrication time that was faster than that of the turret punch. The parts could be nested closer, thereby decreasing the scrap produced by the process and further reducing costs.

Rapid Prototyping, Molding, and Casting

In addition to the enhancements in traditional machining, new rapid prototyping technologies are emerging that have revolutionized the concept of going from a computer model to a finished prototype part. Rapid prototyping machines "print" or build the 3D parts directly from the CAD 3D solid model using polymer materials. APL currently uses two dominant rapid prototyping technologies to prototype parts: stereolithography (SLA) and fused deposition modeling (FDM). SLA uses a laser to activate UV curing epoxy resins in thin, precisely defined layers to build the part; FDM uses small injection nozzles to lay down thin layers of melted acrylonitrile-butadiene-styrene thermoplastic polymer or casting wax to build the part.

Both techniques employ software that imports CAD geometry files and then automatically slices the part geometry data into thin layers to produce the program instructions required to build the part layer by layer, including any necessary temporary support structures. Whereas SLA offers precise control of fine detail, FDM has less resolution but builds sturdy models that can be used as working models or in some cases as prototype parts. By directly producing parts from CAD data files, rapid prototyping technology significantly reduces the time and cost associated with building prototype models to visualize designs and test fit, form, and function. For example, the fixture shown in Fig. 8 was produced in less than 6 hours from a Pro/E solid model using SLA, for a total cost of $350. To produce such a complex, high-precision part by machining would have cost more than 10 times as much and taken significantly longer.

Low-cost prototyping opens the door to polymer molding and metal casting technologies that, coupled with finish machining operations, promise significant savings in cost and time for some parts. TSM has been developing simple polymer molding technologies and now can produce a variety of components using room-temperature vulcanizing silicone molds, lost wax casting techniques, spin casting processes, and injection molding technology. One impressive prototype component is the "fly eye" lens system shown in Fig. 9.

Along with the APL Space Department, TSM is evaluating the use of investment casting for electromechanical housings and related packaging hardware. Several titanium mounts were machined for the TIMED Doppler Interferometer (TIDI) telescope. The mount was very difficult and expensive to machine, hence it was considered an excellent test case to explore the feasibility of casting technology. A telescope mount master was prototyped directly from the Pro/E solid model using an investment casting wax. The wax

Figure 8. Stereolithography was used to produce this complex vacuum fixture used to hold individual lenses in place for bonding to make a "fly eye" lens assembly.

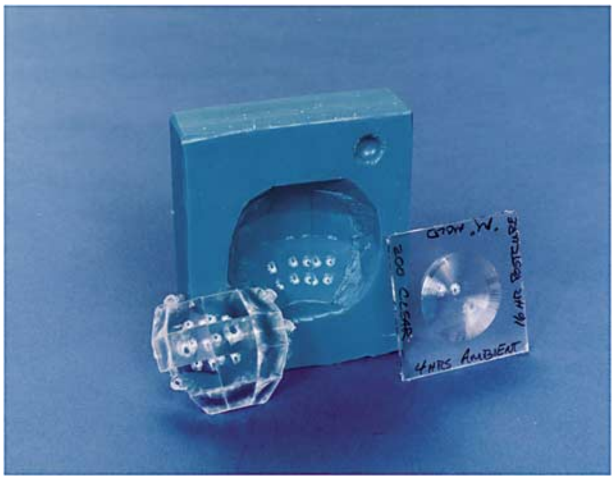

Figure 9. After using the fixture shown in Fig. 8 to produce the fly eye lens assembly from individually machined lenses, a room-temperature vulcanizing silicone mold, shown with uncut lens and molded lens assembly, was used to reproduce the lens assemblies.

master was sent to a foundry where an investment casting mold was made and the part forged. Once the initial titanium casting was formed, it was subjected to hot isostatic pressing to reduce the internal porosity and then heat-treated to obtain specific mechanical properties. Figure 10 shows the finished titanium casting of the TIDI telescope mount. Some detail on the geometry was purposely eliminated so that finish machining could be explored. Each unit cost $450 to cast, whereas the total cost to machine this housing was approximately $18,500 owing to tight tolerances and features that were difficult to machine. (Note: Not all of this difference in cost will be realized once finish machining of the cast part is factored in.)

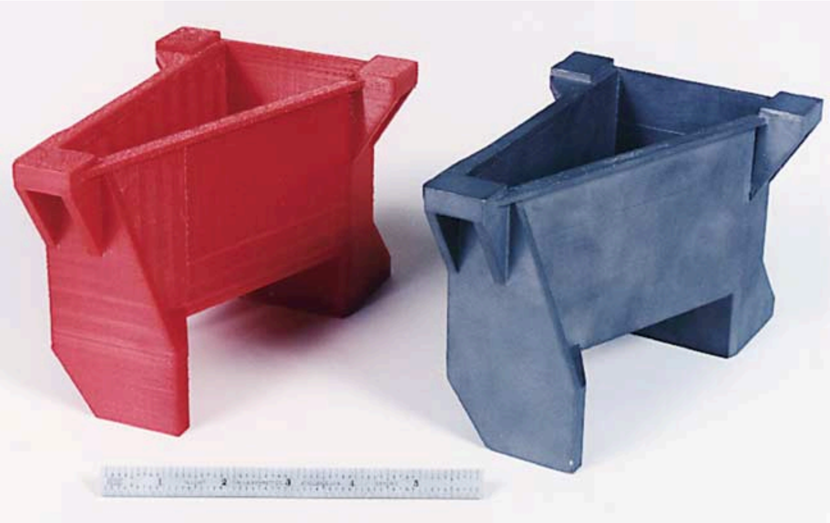

Figure 10. Titanium casting of the TIDI telescope housing (right) was produced from a rapid prototyped casting wax model (left) using an investment casting approach in combination with hot isostatic pressing.

For the primary alloys of interest at the Laboratory—aluminum, magnesium, titanium, and steel—an impressive variety of complex geometry parts can be cast containing features like holes, slots, bevels, bosses, thin walls, and knife edges. Dimensional tolerances of ±127 μm are possible, and many parts can be used as cast with no additional machining. Additional savings can be achieved through parts consolidation. Even with finish machining operations, cast parts offer significant potential for cost savings. For many years, the benefits of near–net-shape casting have been offset by the reduction in material properties that results from the casting process. New postprocessing methods, such as hot isostatic pressing, combined with heat treatments and new design approaches, show promise for producing materials with acceptable properties to meet application requirements.

FUTURE TRENDS

Computer automation and information technology will continue to have a strong impact on the product development process and the tools available to execute it in the future. The impact will extend beyond simple enhancements to make tools easier to use, faster, and more accurate. Technology will also significantly alter the way that product development is accomplished. The use of sophisticated 3D and solid design software will proliferate beyond elite engineers and designers. Information technology will be used to provide functionality that streamlines complex design projects and large assembly management. Enterprise connectivity and data management will be high priorities.

In addition, more tools will be integrated into the design software "suite." The solid modeling package will have seamless interfaces with structural, thermal, dynamic, and a host of other engineering analysis tools, enabling automated optimization of designs. Also, motion analysis simulation software will be able to show how mechanism and machine designs function. As an extension of this advance, human factors analysis programs will allow simulation of the human–machine interface to optimize ergonomics, safety, and ease of maintenance.[6] All of these innovations will lead to the ability to virtually prototype, test, and evaluate a design through computer simulation.

The main enhancements expected in CAM are improvements in capabilities for the programming of tool paths and work piece setups to optimize the machining process relative to the part design specifications and the machine tool characteristics. "Intelligent assistants" to identify and recommend design changes to promote design-for-manufacture are another feature that is likely to appear in future CAM packages.

Machine tools will continue to be modified to accommodate computer-controlled machining processes, increase speeds, and increase accuracy. High-speed machining will become more commonplace as costs decrease.

Laser technology applications will rapidly increase in sheet metal fabrication, welding, marking, heat-treating processes, and the fabrication of micro- and mesoscale parts for miniature devices. The penetration of laser technology into these processes is being fueled by the development of lower-cost, higher-power systems with improved operating and maintenance characteristics. In addition, process technologies are constantly being developed to improve the quality and economics of lasers. For example, surface alloying techniques have been developed where a laser impinges on the surface of a metal in the presence of alloying compounds to create a thin alloyed layer with the desired characteristics.[7] Such laser surface alloying techniques can be used to replace less effective cladding or coating technologies.

As miniaturization trends continue to shrink electronics systems, the demand for micro- and mesoscale mechanical systems will increase. Lasers and EDM machining technology will play a significant role in supporting micro- and mesoscale machining, especially for systems demanding engineering materials other than the silicon materials commonly used to make microelectromechanical systems devices.

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